Massive remnant of evolved cometary dust trail detected in the orbit of Halley-type comet 55P/Tempel-Tuttle

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ABSTRACT

There is a sub-population of Leonid meteoroid stream particles which appear to form a region of enhanced number density along the path of the stream. This structure has been detected in the vicinity of the parent comet and its variation from one apparition to the next has been traced. Some of this dust is found in regions dynamically inaccessible to particles experiencing no other perturbing forces than ejection from the nucleus and radiation and has dimensions exceeding by an order of magnitude that expected for a cometary dust trail. A significant amount of known comet 55P/Tempel-Tuttle debris is in this component, called a "filament". As filament particles are of a size comparable to those found in trails, the emission ages of the particles comprising the filament must be intermediate between the age of the current trail particles (which have not been observed) and the age of the background particles comprising the annual showers. The most likely explanation for this structure is planetary perturbations acting differently on the comet and large particles while at different mean anomalies relative to each other.

Subject headings: comets: general - dust, extinction - meteors, meteoroids

1. INTRODUCTION

Comet 55P/Tempel-Tuttle is in an unusual Halley-type orbit passing close to Earth’s orbit every 33 odd years since over 1000 years. Historic accounts of meteor storms have mapped out a dust trail behind the comet and outside the comet orbit (Sekanina 1975, Yeomans 1981).

Here, we report the detection of a dust Filament that appears to be a later stage in the orbital evolution of these dust trails, containing as much mass as the annual shower debris. This new structure was traced out by unusual Leonid shower activity in the years preceding the February 1998 return of the comet, and was again detected in November of 1998. The unusual activity was recorded by forward meteor scatter techniques, each year adding a new cross section of the dust distribution. We also applied multi-station photographic techniques for measuring the direction of motion of individual meteoroids at Earth and found the orbits to be dispersed and systematically displaced from year to year along the comet orbital plane. Planetary perturbations are implied and a relatively old age.

Moreover, we now find that this Filament is not a unique feature to the distribution of ejecta of comet 55P/Tempel-Tuttle. A similar structure was detected earlier in the orbit of Halley-type comet 109P/Swift-Tuttle, the only other Halley-type comet that comes close enough to Earth's orbit.

The presence of this older dust has important implications for understanding the orbital evolution of the cometary dust trails that have been detected in the orbit of short-period comets from the thermal emission of warm dust (Davies et al. 1984, Sykes et al. 1986, Sykes & Walker 1992).

2. OBSERVATIONS AND RESULTS

2.1. Trail cross section and particle size distribution.

After 25 years of normal annual rates, unusual Leonid shower activity was first detected in 1994 (Jenniskens 1996). Ever since, Leonid outbursts have been recorded by visual observers and by automatic meteor counting stations using the technique of forward meteor scattering (Yrjölä & Jenniskens 1998). Here, we report on the counts of four Global-MS-Net stations in Finland (I. Yrjölä - ●), Belgium (M. de Meyere - o), Ghent University, Belgium (Pierre de Groote - ❑), and the U.S.A. (Paul Sears - •). The meteor counts in excess of sporadic background rates are shown in Fig. 1, as a function of time in terms of the Earth's position in its orbit (the solar longitude). The relative activity levels and the shape of the activity curves are in good agreement with the meteor counts by visual observers published elsewhere (e.g. Jenniskens 1995, 1996; Brown & Arlt 1997; Arlt 1998, Langbroek 1999). The time of the peak activity, the level of activity and the duration of the shower are summarized in Tab. 1.

The activity curves are usually well described by a profile of the generic shape (Jenniskens 1995):

$$ZHR = ZHR_{max} \quad 10^{\mid 0.869\,(\lambda o\, -\, \lambda omax)/\Delta\Omega \mid} \qquad (1)$$

where ZHR is the Zenith Hourly Rate that describes visual meteor counts by a standard observer under good observing conditions (star limiting magnitude = 6.5) and a radiant position in the zenith. A dashed line in Fig. 1 is such a profile for an assumed nodal dispersion of $\Delta\Omega = 0.8^{o}$. The near-constant width at positions in the dust trail pass Earth's orbit years apart implies a trail, ribbon or filament-like structure. In this paper, we will refer to this structure as the “Leonid Filament”.

The nodal dispersion defines the thickness of this Filament, taking into account that the Leonid shower cuts the Earth’s orbit at a shallow angle of 18.1^{o} (Kresák & Porubcan 1970). The full width at half maximum of that Filament, perpendicular to the comet orbit is FWHM = $6x10^{5}$ km. This compares to a width of a six times higher FWHM = $3.5x10^{6}$ km for the annual shower debris (Jenniskens 1996).

A similar broad dust component was observed during the previous 1965 encounter, first in 1961 (Jenniskens 1996). At that time, too, the outburst was rich in bright meteors and occurred when the Earth was outside the comet orbit and in front of the comet. If we assume that both accounts describe the same debris, then the difference in minimum distance between comet and Earth’s orbit in 1994 and 1961 (0.0033 versus 0.0080 AU) sets a lower limit to the dispersion perpendicular to the Earth’s orbit: > $7x10^{5}$ km. This value is of the same order as the measured thickness.

The Filament appears to be confined to the position of the comet. There is no sign of this dust component in the compilations of Leonid meteor shower observations in the period 1981-1991 (Jenniskens 1996, Koseki 1993, Brown 1994). The 1994 and 1961 returns represent a sudden onset. The component extends at least one year after passage of the comet, with strong returns observed in 1965 and recently in 1998. Less certain observations exist for the period 1966-68 (Tab. I). If we assume that the debris can be detected for a period of 8 years around the passage of the comet, then it is dispersed only over about 1/5 of the comet orbit. In contrast, the annual shower debris is evenly distributed along the comet orbit, with no strong enhancement near the position of the comet (Jenniskens 1996).

Peak rates more or less gradually increase to a peak some time behind the comet, and gradually decreases afterwards (Fig. 2), but activity in 1994 and 1961 stands out as being unusually intense. The similar behavior of the 1965 and 1998 returns is striking. Note that also the time of the peak relative to the comet node follows the behavior of the 1965 return, perhaps with the exception of the intense 1994 return (Fig. 2). Comet 55P/Tempel-Tuttle had an ascending node at 235.12 deg. in 1965 and at 235.26 deg. in 1998 (J2000).

In all those years, the showers were relatively abundant in bright meteors with corrected rates increasing by only a factor of $\chi = N(m+1)/N(m) = 1.4\text{-}2.3$ per magnitude interval, the population index. In comparison, $\chi = 3.0\pm0.2$ during past Leonid storms (Jenniskens 1995). Corresponding values for the differential mass distribution index are $s \sim 1.6$ and $s = 2.19$, respectively. There is some indication that the largest particles are found dominantly near the position of the comet, with $\chi = 1.5 \pm 0.1$ in 1965 and 1998, behind the position of the comet.

As a result, the total mass in the Filament for particles between 10^{-6} and 10^{2} g (-5 to +7 magnitude Leonids) is about 1×10^{15} g (following the procedure in Jenniskens (1994). This is as much as half of the total mass in the annual shower debris (2×10^{15} g) and significantly more than the 2×10^{13}g estimated for the trail-like structure that is though to cause the Leonid storms. The latter mass estimates are in fact higher than our previous values (Jenniskens 1995), because we incorrectly used an algorithm that broke down for entry velocities close to 72 km/s (with no or little consequences for other showers, hence the error remained unnoticed).

The new mass estimates reported here compare to $10^{11.5-14.5}$ g for the mass estimates of cometary dust trails of short period comets by Sykes & Walker (1992). The dimensions of the Leonid Filament (6×10^{5}, $>7 \times 10^{5}$) are comparable to the widths of the Encke (6.8×10^{5} km) and Schwassmann-Wachmann 1 (7.7×10^{5} km) dust trails, but they are about a factor of 10 larger than other trail widths.

2.2. Individual meteoroid orbits.

During the Leonid return of 1995, 1997, and 1998, we successfully obtained trajectories and orbits of individual meteoroids at the time of the Leonid outbursts. In order to do so, we deployed multi-station networks of batteries of small 35mm cameras. The method is described in Betlem et al. (1998). Results from the 1995 and 1998 campaigns are presented in Betlem et al. (1997 and 1999). In Table 2, we present the trajectory and orbits of 10 Leonids from the 1997 campaign, which was conducted in California with support of members of the California Meteor Society. These data are of lower accuracy because of a full Moon, which results in the detection of only that part of the meteor trail that is bright (and often over exposed). On the other hand, the 1997 data form an interesting sequence in combination with the 1995 and 1998 results.

All radiant positions are plotted in Fig. 3, after correction for the daily changing direction of motion of Earth itself to that at solar longitude $\lambda_o = 235.0$, i.e. Δ R.A. = +0.99°, Δ Decl. = -0.36° per degree solar longitude.

From the relative intensity of annual and outburst components of shower activity, we conclude that a significant fraction of the observed meteors are expected to be part of the outburst component, some 60 % of the1995 Leonids and close to 100 % of those photographed in 1997 and 1998.

Only seven of the 29 radiants measured in 1995 form a dense cluster at R.A. = 153.63±0.11 , Decl. = +21.97±0.03 (J2000). All radiants measured in 1997 are located close to that position, but slightly displaced and centered at R.A. = 153.77±0.11 , Decl. = +22.03±0.06 (Fig. 3). Those of 1998 are displaced from that again, now centered at R.A. = 153.80±0.08 , Decl. = +22.10±0.03.

In all years, the radiant distribution is significantly dispersed. Without good criteria to distinguish between cluster and non-cluster 1995 Leonids, and because of relatively large errors in the 1997 data, it is not possible to state that the dispersion measured in 1995 is significantly different from that measured in 1997 or 1998.

From the radiant and mean speed along the trajectory, the orbital elements are calculated (Tab. 2). The semi-major axis (a) is clustered near and perhaps slightly longward of that of the comet, as expected if ejection velocities are low. The observed dispersion in radiant positions translates into a significant dispersion in the orbital elements. The systematic yearly shift in radiant position returns, for example, in the graph of perihelion distance versus inclination as a gradual shift in both q and I from year to year (Fig. 4).

3. DISCUSSION

3.1. A new Structure.

The photographed meteors probe particles of mass about 0.3 gram, or a diameter of order 1 cm, using the general formula for the mass of a given meteor brightness by Jacchia et al. (1967). Meteoroids of that size are typically associated with cometary dust trails , rather than tails(Sykes & Walker 1992). Kresak (1993) first argued a generic link between cometary dust trails and meteor storms.

Our initial interpretation of the meteor data was that of a classic dust trail (Jenniskens 1995). We assumed that the relatively low peak activity in years before passage of the comet by perihelion might come on account of an asymmetry that is common in dust trails. Dust trails tend to be more extended behind the comet (Sykes & Walker 1992).

This asymmetry is generally understood as a result of the effect of ejection velocities causing asymmetric distributions in semi-major axis (Plavec 1955) and the effect of radiation forces that effectively lower the radial force from the Sun's gravity, putting the particles in wider orbits (Kresák 1976). After one return, the grains tend to lag the comet, an effect that is most severe for the smallest grains. One would expect a gradually increasing population index along the dust trail.

We now find that the population index increases rather than decreases when approaching the comet position and is always significantly less than observed during the Leonid storms of 1966 and 1866/67 (Tab. II).

It was observed earlier (Jenniskens 1996, Brown et al. 1997) that multiple dust components are recognized in the available radar observations of the 1965 return (McIntosh & Millman 1970), the Filament being distinct from other less dispersed structures. This was seen again during the return of 1998 (Jenniskens 1999). The similar population index and duration of the outbursts in the years 1994-1998 gives further support to the hypothesis that the 1961 and 1965 outbursts were caused by the same dust feature (the Filament).

Particles ejected isotropically with some ejection velocity will, in the absence of radiation pressure, disperse ahead and behind the comet in its orbit. The particles trailing behind the comet do so because their semi-major axes are larger and they consequently have smaller angular velocities. Looking down on the orbit from above, these particles would appear outside of the orbital path, away from the sun. Particles ahead of the comet have, in this example smaller semi-major axes, higher angular motions and would appear interior to the comet orbit when seen from above. When particles are seen away from the comet in the other quadrants, this is evidence for other forces in operation. In this case, these other forces must be planetary perturbations.

The significance of planetary perturbations follows also from the relatively large dispersion of the radiants and the node. The observed thickness of the Filament and radiant dispersion are consistent with ejection velocities of order 90 m/s. This is a factor of three higher than the Vej ~ 30 m/s calculated from the classical theory of ejection by water vapor drag assuming nominal density of 1 g/cm3, ejection at perihelion and 0.1 gram particle(Whipple 1951, Jones & Brown 1997). Note that the much smaller nodal dispersion of meteor storms implies lower ejection velocities Vej ~ 5 m/s. One possible explanation is that the Filament grains may have had an episode of better gas-to-dust coupling by ejection from depressed active areas (Jones 1995, Jones & Brown 1997), or by being flake or needle shaped (Gustafson 1989), or perhaps because they are accelerated by ice grain ejection (Steel 1994). However, such a high ejection velocity would imply rapid dispersion along the comet orbit. A single revolution would be sufficient to spread the dust as many years before and behind the comet position as observed. And subsequent revolutions would increase that dispersion. That only leaves the possibility that the dispersion is a signature of planetary perturbations and a sign of relatively high age.

As filament particles are of a size comparable to those found in trails, the emission ages of the particles comprising the filament must be intermediate between the age of the current trail particles (which have not been observed) and the age of the background particles that comprise the annual showers.

3.2. Evolved Dust Trails.

Recently, Asher et al. (1999) argued that the Filament is caused by ejection of dust grains into the 5/14 mean-motion resonance with Jupiter, principally during the perihelion passage of comet 55P/Tempel-Tuttle in 1333. This trapping in resonances has the effect that particles do not spread uniformly around the orbit, but instead librate about a resonance centre within the main stream. The particles remain concentrated in space, but differential precession between the comet orbit and the orbits of these resonant particles can lead to increasing differences in the orbital elements over time.

Our observations lend support to such a scenario, but also support the scenario proposed by Jenniskens (1998) that the grains were ejected with small ejection velocities and were protected from close encounters with the planets by virtue of the comet librating around an orbital resonance. In this case, it is the comet's motion that results in a temporary accumulation of debris, rather than the entrapment of meteoroids in orbital resonances.

Rather than being near the 2:5 orbital resonance with Uranus (Williams 1997), the comet is presently librating around the 5:14 resonance with Jupiter and the 8:9 resonance with Saturn. Librations around higher order resonances are a common phenomenon. Such librations around mean-motion resonances tend to stablize the orbit for some time and protect the region near the comet for close encounters with the planets. The comet itself shows the most severe perturbations during relatively close (< 1 AU) encounters with Jupiter and Saturn. Close encounters over the 2000 year interval studied by Yeomans et al. (1996) tended to cluster near 0.55 AU or 0.85 AU, rather than values in between, while both planets can approach the comet orbit closer. This is a signature of the orbital resonances and shows that the region nearest to the comet has been free from close encounters for some time.

It is especially the larger grains that can survive in this region: the smaller grains are ejected with higher ejection velocities and tend to spread over time towards parts of the orbit that are prone to close encounters. This may account for the less steep size distribution and subsequent relative abundance of bright meteors.

This interpretation suggests that the Leonid Filament represents an accumulation of matter from different perihelion returns. The dust Filament will continue to build up until the end of a libration cycle and a transition to another orbital resonance. From the relative mass content of dust trail and filament, that accumulation of matter must have occurred over at least10-100 perihelion returns, which puts the age of the Filament at about 10^3 years. This is equivalent to the time scale over which Halley-type comet 109P/Swift-Tuttle tends to librate around a mean-motion resonance: 5.10^3 years (Chambers 1997).

Unless the matter is distributed in a thin sheet, rather than the more or less cylindrical structure suggested by the similarity of the1998 and 1965 returns, the total mass calculated for the Filament is much larger than the typical ejecta of a single perihelion return. Hence, our interpretation of the observations argues against the hypothesis of Asher et al. (1999) that ejection of a single perihelion return is responsible for the observed shower, unless that return was unusually (10 to 100 times more) active.

3.3. Filaments as a generic Feature of Halley-type comets.

Centered on the return to perihelion of comet 109P/Swift-Tuttle, a series of meteor outbursts were observed that traced a similar meteoroid debris component, called the Perseid Filament (Brown & Rendtel 1997, Jenniskens et al. 1998). Here, we point out the similarities between the Perseid Filament and the Leonid Filament, which are summarized in Tab. 3.

Common features are the low and similar population index χ, the amount of time that the matter is detected in front of and behind the comet, and the total amount of mass in the structure (assuming its dispersion perpendicular to the Earth's path is as large as that of the Leonid Filament).

Moreover, there is a remarkable similarity in the radiant structure. In our analysis of the Perseid shower, we discovered the same dynamic pattern as found in this paper: the radiants are dispersed in individual years and the centroid in each year is significantly displaced from one year to the other along a line at an angle to the ecliptic plane (Jenniskens et al. 1998).

The thickness of the Perseid Filament is a factor of 4 less than that of the Leonid Filament. Perhaps this reflects the fact that 109P/Swift-Tuttle is in a 1:11 mean-motion resonance with Jupiter, rather than librating around a higher order resonance. Coincidentally, the orbital period is 4 times larger than that of 55P/Tempel-Tuttle.

Comet 109P/Tempel-Tuttle is the only other Halley-type comet that approaches Earth's orbit close enough to observe a Filament structure. Hence, Filaments may be a common feature of the orbital evolution of cometary debris of Halley-type comets, and perhaps also of other type comets. Much of the mass loss of these comets is accumulated in this massive remnant. Hence, this is a significant phase in the orbital evolution of large cometary dust grains.

Observations from the 1966-1969 period are not abundant, but do suggest that the Filament may continue to be visible at somewhat lower level of activity than in 1998, at least until 2002.

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Fig. 1. __ Leonid meteor counts by forward meteor-scattering during the different years prior to perihelion passage of comet 55P/Tempel-Tuttle.

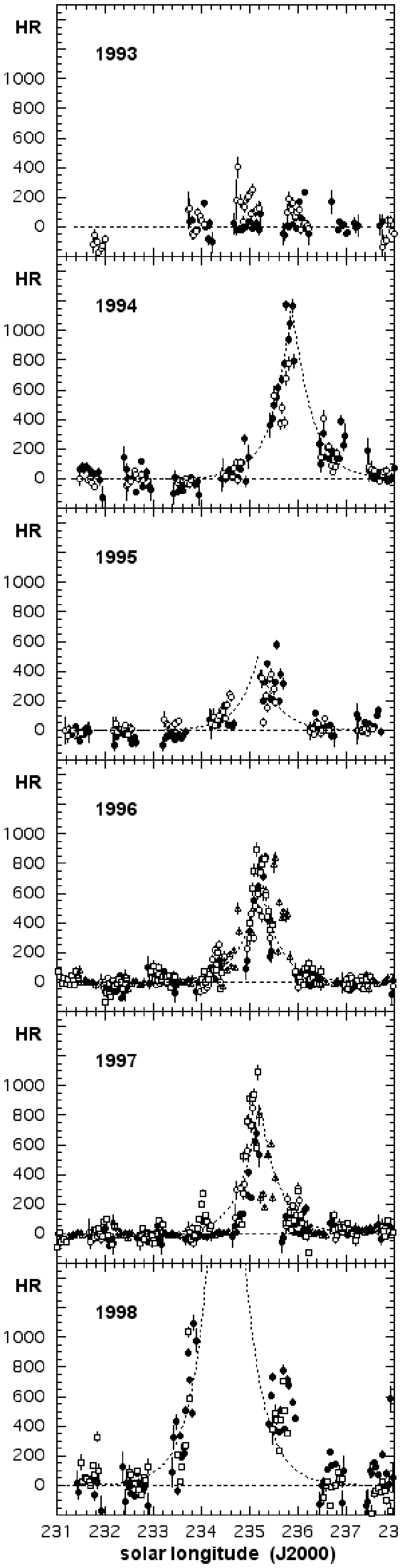

Fig. 2. __ Peak activity and time of maximum of Leonid Filament outbursts between 1961-1968 and 1994-1998.

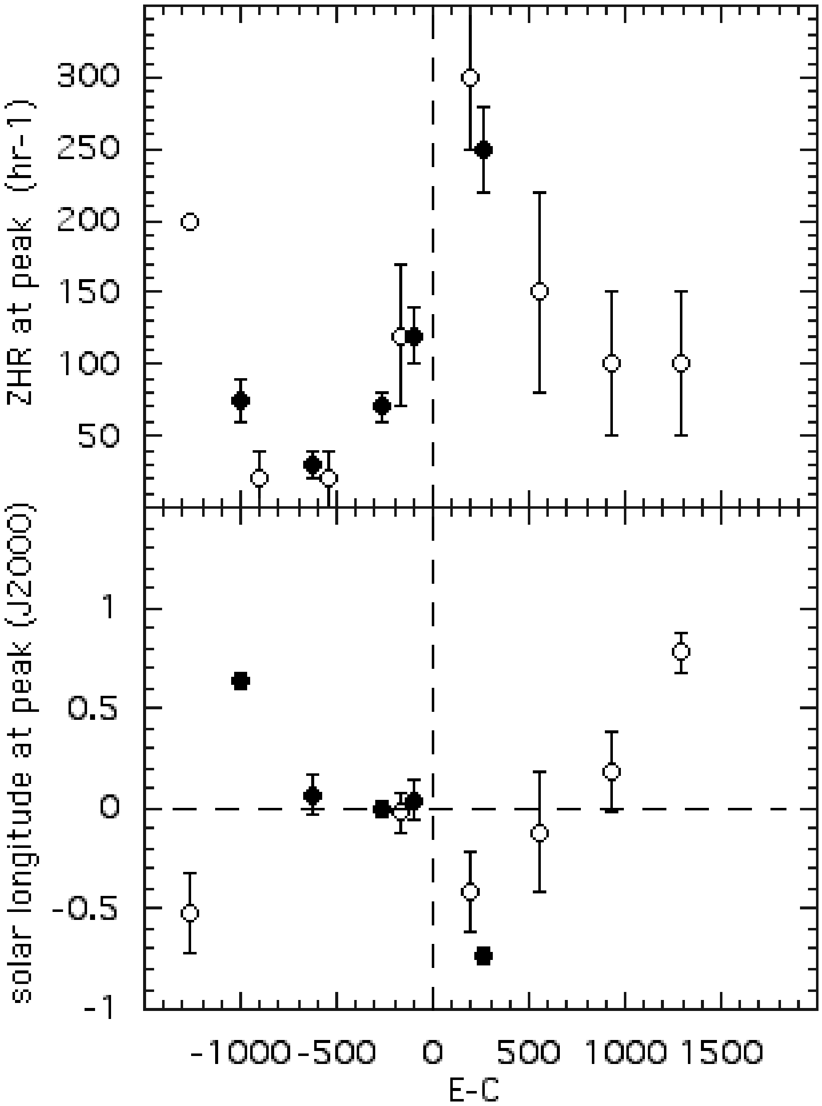

Fig. 3. __ Radiant distribution of Leonid meteors in 1995 (open squares- Betlem et al. 1997), 1997 (black dots - this paper), and 1998 (open dots - Betlem et al. 1999).

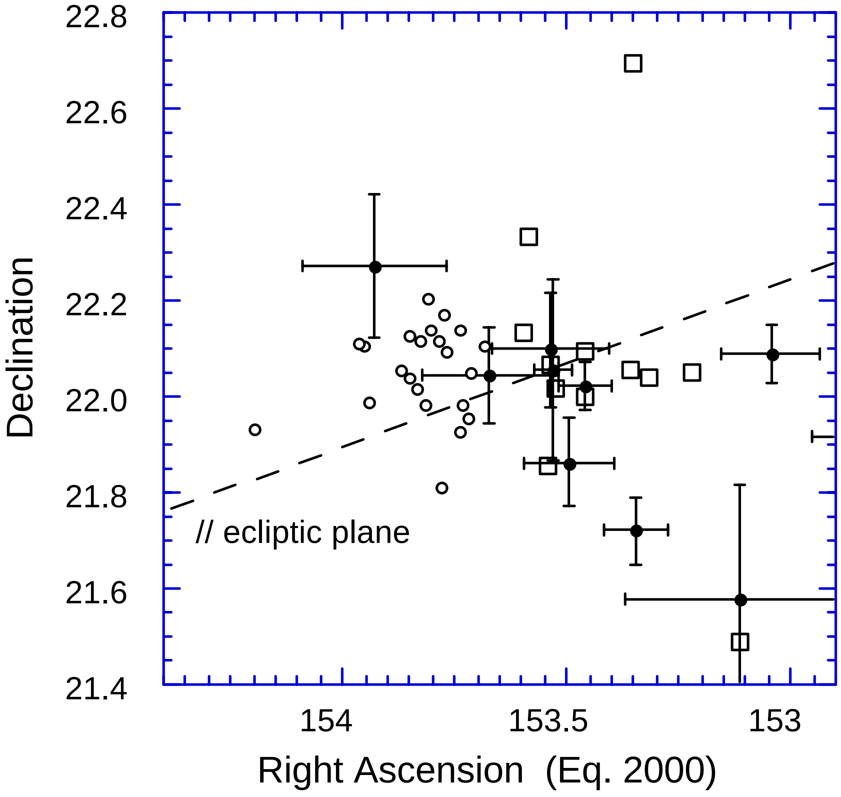

Fig. 4. __ Distribution of orbital elements (symbols as in Fig. 3).

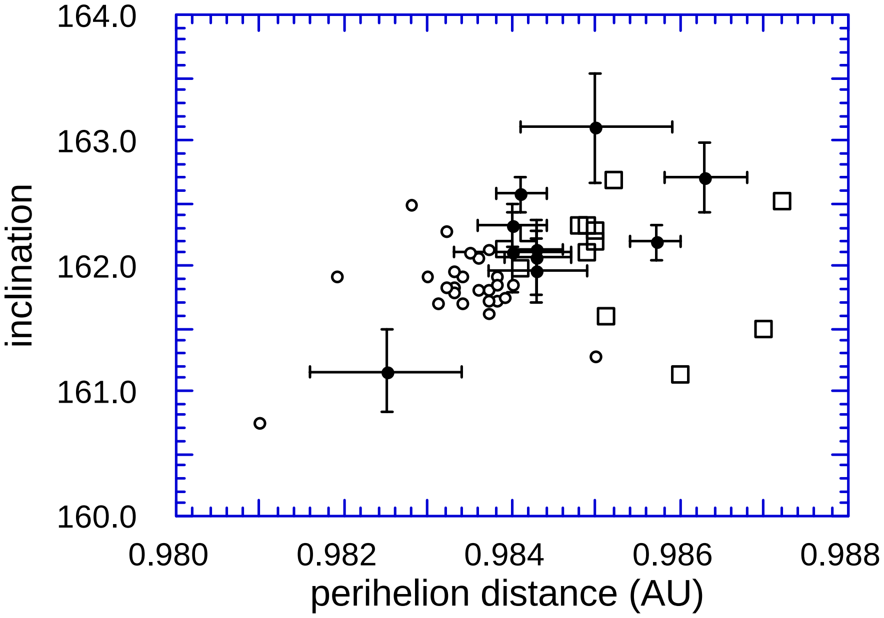

Fig. 5. __ Cartoon showing the new Filament structure in relation to other known cometary dust features.

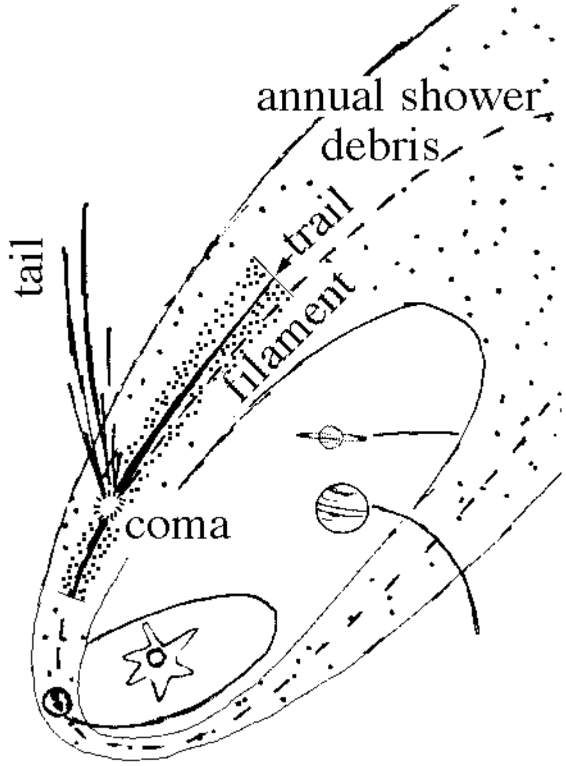

TABLE I

Cross section and particle size distribution for the Leonid Filament

Year	E-C (days)	FWHM (deg.)	χ	Peak λo J2000	ZHR$_{max}$ (hr-1)	$\rho\bullet_{max}$ (10^{-24} g/cm-3)	Peak λo J2000	ZHR$_{max}$ (hr-1)	ρ_{max} (10^{-24} g/cm-3)
				1965 return:			*1998 return:*		
1981-91	-	-	-				-	<3	<0.3
1960	-1630	-	-	-	<10	<1			
1993	-1358	-	-	-	<10	<1			
1961	-1265	-	2.3	234.6±0.2	~200	~5			
1994	-993	0.8±0.1	2.1±0.3				235.90±0.04	75±15	3.2
1962	-900	-	-	-	<40	<2			
1995	-628	~0.8	2.0±0.3				235.33±0.10	30±10	1.7
1963	-535	-	-	-	~20	~1.1			
1996	-262	0.7±0.2	1.9±0.9				235.26±0.04	70±10	5.3
1964	-170	-	-	235.1±0.1	~120	~11			
1997	-103	0.6±0.1	-				235.3±0.1	120±20	9.1
1965	+196	~0.8	~1.7	234.7±0.2	~300	40			
1998	+262	0.8±0.1	1.5±0.1				234.52±0.01	250±20	…
1966	+561	-	-	235.0±0.3	<150	<10			
1967	+926	-	-	235.3±0.2	~100	~8			
1968	+1291	-	-	235.9±0.1	~100	~8			
1969	+1656	-	-	-	<10	<1			
1970	+2021	-	-	-	<10	<1			

Sources: Jenniskens (1996), Langbroek (1996, 1999), Brown & Arlt (1997), Arlt (1998).

TABLE II

Osculating Orbital Elements of 1997 Outburst Leonids at the Epoch of the Meteor

Time (1997 Nov 17)	R.A.[a] (deg)	Decl.[a] (deg)	V• (km s-1)	Hb (km)	He (km)	mv (mag)	M/C_DS (g/cm-2)	1/a (AU-1)	q (AU)	I[a] (deg)	ω[a] (deg)	Ω[a] (deg)
9:22:23	153.63±0.04	+21.82±0.19	71.9±0.4	114.1	91.6	-1	0.14	+0.08±0.04	0.9843	162.06	171.72	235.0987
10:02:01	152.91±0.17	+21.87±0.16	71.8±0.5	113.0	96.6	-1	0.04	+0.10±0.04	0.9863	162.71	174.32	235.1264
10:56:58	153.70±0.13	+22.04±0.12	71.6±0.7	109.3	97.4	0	0.18	+0.10±0.07	0.9843	161.96	172.18	235.1649
10:50:30	154.13±0.16	+22.20±0.15	70.1±1.0	106.0	81.6	-4	-	+0.23±0.09	0.9825	161.16	170.31	235.2024
11:54:46	153.70±0.10	+21.79±0.09	71.4±0.4	115.9	91.6	-2	-	+0.12±0.04	0.9840	162.32	171.90	235.2054
12:00:33	153.32±0.26	+21.50±0.24	71.9±0.7	117.2	92.9	-3	0.01	+0.08±0.07	0.9850	163.10	172.92	235.2094
12:11:55	153.26±0.11	+22.01±0.06	71.1±0.4	112.2	84.5	-10	0.09	+0.15±0.04	0.9857	162.19	173.53	235.2174
12:25:24	153.57±0.07	+21.64±0.07	71.0±0.5	114.4	94.1	-1	0.18	+0.16±0.04	0.9841	162.57	171.96	235.2268
12:45:54	153.91±0.15	+21.96±0.10	72.3±1.5	114.6	86.5	-2	0.006	+0.02±0.14	0.9840	162.11	172.10	235.2412
13:03:05	153.71±0.06	+21.93±0.05	71.4±0.7	112.1	89.4	-2	0.02	+0.11±0.07	0.9843	162.12	172.26	235.2532

a) geocentric radiant, Equinox J2000

TABLE III
Comparison of Leonid and Perseid Filament

	Leonid Filament	Perseid Filament
size distriution index (s)	1.6±0.2	1.7±0.1
Width	$6\ 10^{5}$ km	$1.4\ 10^{5}$ km
In-plane dispersion	$>7\ 10^{5}$ km	$>6\ 10^{5}$ km
Length	8 years	8 years
Peak flux (ρ)	$4\ 10^{-23}$ g/cm^{3}	$7\ 10^{-23}$ g/cm^{3}
Mass	$1\ 10^{15}$ g	$5\ 10^{14}$ g